Plan

- Goals for this Week
  - » Grading criteria breakdown for MINIX projects (see project web page).
    - – Talk about demos and how to prepare
    - – First set of demos this Thursday afternoon.
  - » Overview of next project (post details tonight).
  - » Finish Synchronization
  - » Thursday - discuss next project and MINIX review/ overview in the context below:
    - – How to add a system call
    - – Services in MINIX
      - Synchronization Service
    - – Create am appliation
- Next Week - deadlock

Demos

- 3:30 – 5:30 – first 5-6 demos (later today)
- Preparation (show & tell)
  - » 2 precompiled kernels
    - – By boot image or if you like 2 separate VM whatever you like.
  - » 1 prepared document to tell me what is working what is not – overview what you did (5 minutes)
- How will it work (details)
  - » Show Data Structures in code
  - » Show Functionality added in code/kernel
  - » Show that it runs
  - » Demonstrates your testing strategy
  - » Compile & run (this will be done last)

Overview MINIX (more Thu)

- Small OS – Microkernel 4,000 lines of code (src/kernel)
- Windows XP – 5 millions lines of code
- Linux – 3 millions lines of code

Next Project

- Add System Call
- Add a service (see how this fit in shortly)
  - » It is a synchronization service
  - » Waking up and putting processes to sleep
- Write a simple application program that use this new service.
- How it fits in:


CSCI [4|6]730 Operating Systems

Synchronization Part 2

Chapter 6: Process Synchronization Part II

- How does hardware facilitate synchronization?
- What are problems of the hardware primitives?
- What is a spin lock and when is it appropriate?
- What is a semaphore and why are they needed?
- What is the Dining Philosophers Problem and what is 'a good' solution?

Hardware Primitives

*Many modern operating systems provide special synchronization hardware to provide more powerful **atomic** operations*

- `testAndSet( lock )`
  - atomically reads the original value of lock and then sets it to true.
- `Swap( a, b )`
  - atomically swaps the values
- `compareAndSwap( a, b )`
  - atomically swaps the original value of lock and sets it to true when they values are different
- `fetchAndAdd( x, n )`
  - atomically reads the original value of x and adds n to it.

Hardware: testAndSet();

```
boolean testAndSet ( boolean &lock )
  {
  boolean old_lock = lock ;
  lock = true;
  return old_lock;
  }
```

```
// initialization
lock = false ; // shared -- lock is available
void deposit( int amount )
   {
   // entry to critical section - get the lock
   while( testAndSet( &lock ) == true ) {} ;
   balance += amount // critical section
   // exit critical section - release the lock
   lock = false;
   }
```

- If someone has the lock (it is TRUE) wait until it is available (until some-one gives it up, sets it to false).
- Atomicity guaranteed - even on multiprocessors

Hardware: Swap();

```
void Swap( boolean &a, boolean &b )
  {
  boolean temp = *a ;
  *a = *b;
  *b = temp;
  }
```

```
// initialization
lock = false ; // global shared -- lock is available
void deposit( int amount )
   {
   // entry critical section - get local variable key
   key = true; // key is a local variable
   while( key == true ) Swap( &lock, &key );
   balance += amount // critical section
   // exit critical section - release the lock
   lock = false;
   }
```

- Two Parameters: a global and local (when lock is available (false) get local key (false)).
- Atomicity guaranteed - even on multiprocessors
- Bounded waiting?
  - No! How to provide?

Hardware with Bounded Waiting

- Need to create a waiting line.
- Idea: Dressing Room is the critical section, only one person can be in the room at one time, and one waiting line outside dressing room that serves customer first come first serve.
  - `waiting[n]` : Global shared variable
  - `lock`: Global shared variable
- Entry get a local variable 'key' and check via `testAndSet()` if someone is 'in' the dressing room

Hardware with Bounded Waiting

```
// initialization
lock = false ;   // shared -- lock is available
waiting[0.. n-1] = {false} ; // shared -- no one is waiting
void deposit( int amount )
   {
   // entry to critical section
   waiting[tid] = true; // signal tid is waiting
   key = true; // local variable
   while( ( waiting[tid] == true ) and ( key == true ) )
         key = testAndSet( &lock );
   waiting[tid] = false; // got lock done waiting
   balance += amount     // critical section

   // exit critical section - release the lock
   j = (tid + 1) mod n; // j is possibly waiting next in line
   while( ( j != tid ) and ( waiting[j] == false ) )
         j = (j + 1) mod n;   // check next if waiting
   if( j == tid )              // no one is waiting unlock room
         lock = false;
   else
         waiting[j] = false  // hand over the key to j
   }
```


Hardware Solution: Proof "Intuition"

- **Mutual Exclusion:**
  - A thread enters only if it is waiting or if the dressing room is unlocked
    - First thread to execute `testAndSet( &lock )` gets the lock all others will wait
    - Waiting becomes false only if the thread with the lock leaves its CS and only one waiting is set to false.
- **Progress:**
  - Since an exiting thread either unlocks the dressing room or hands the 'lock' to another thread progress is guaranteed because both allow a waiting thread access to the dressing room
- **Bounded Waiting:**
  - Leaving threads scans the waiting array in cyclic order thus any waiting thread enters the critical section within n-1 turns.

Synchronization Layering

- Build higher-level synchronization primitives in OS
  - » Operations that ensure correct ordering of instructions across threads
- Motivation: Build them once and get them right
  - » Don't make users write entry and exit code

Monitors ☺ Locks Semaphores
Condition Variables

Loads Stores Test&Set
Disable Interrupts

Locks

- Goal: Provide mutual exclusion (mutex)
  - » The other criteria for solving the critical section problem may be violated
- Three common operations:

Allocate and Initialize

```
pthread_mutex_t mylock;
mylock = PTHREAD_MUTEX_INITIALIZER;
```

Acquire

Acquire exclusion access to lock; Wait if lock is not available

```
pthread_mutex_lock( &mylock );
```

Release

Release exclusive access to lock

```
pthread_mutex_unlock( &mylock );
```


Lock Examples

- After lock has been allocated and initialized

```
void deposit( int amount )
  {
  pthread_mutex_lock( &my_lock );
  balance += amount; // critical section
  pthread_mutex_unlock( &my_lock );
  }
```

- One lock for each bank account (maximize concurrency)

```
void deposit( int account_tid, int amount )
  {
  pthread_mutex_lock( &locks[account_tid] );
  balance[account_tid] += amount; // critical section
  pthread_mutex_unlock( &locks[account_tid] );  }
```


Implementing Locks: Atomic loads and stores

```
typedef struct lock_s
  bool lock[2] = {false, false};
  int turn = 0;

void acquire( lock_s *lock )
  lock->lock[tid] = true;
  turn  = 1-tid;
  while( lock->lock[1-tid] && lock->turn ==1-tid )

void release( lock_s lock )
  lock->lock[tid] = false;
```

- Disadvantage: Two threads only

Implementing Locks: Hardware Instructions (now)

```
typedef boolean lock_s;

void acquire( lock_s *lock )
  while( true == testAndSet( theLock ) ) {} ; // wait

void release( lock_s lock )
  lock = false;
```

- Advantage: Supported on multiple processors
- Disadvantages:
  - » Spinning on a lock may waste CPU cycles
  - » The longer the CS the longer the spin
    - – Greater chance for lock holder to be interrupted too!

Implementing Locks: Disable/Enable Interrupts

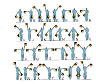
```
void acquire( lock_s *lock )
  disableInterrupts();

void release( lock_s lock )
  enableInterrupts();
```

- Advantage: Supports mutual exclusion for many threads (prevents context switches)
- Disadvantages:
  - » Not supported on multiple processors,
  - » Too much power given to a thread (may not release lock_
  - » May miss or delay important events

Spin Locks and Disabling Interrupts

- Spin locks and disabling interrupts are useful only for very short and simple critical sections
  - » Wasteful otherwise
  - » These primitives are *primitive* -- don't do anything besides mutual exclusion
- Need a higher-level synchronization primitives that:
  - – Block waiters
  - – Leave interrupts enabled within the critical section
  - » All synchronization requires atomicity
    - – So we'll use our "atomic" locks as primitives to implement them

Semaphores

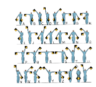


- Semaphores are another data structure that provides mutual exclusion to critical sections
  - » Described by Dijkstra in the THE system in 1968
  - » Key Idea: A data structure that counts number of "wake-ups" that are saved for future use.
    - – Block waiters, interrupts enabled within CS
- Semaphores have two purposes
  - » Mutual Exclusion: Ensure threads don't access critical section at same time
  - » Scheduling constraints: Ensure threads execute in specific order (implemented by a waiting queue).

Blocking in Semaphores

- Idea: Associated with each semaphore is a queue of waiting processes (typically the ones that want to get into the critical section)
- `wait()` tests the semaphore (DOWN) (wait to get in).
  - » If semaphore is open, thread continues
  - » If semaphore is closed, thread blocks on queue
- `signal()` opens the semaphore (UP): (lets others in)
  - » If a thread is waiting on the queue, the thread is unblocked
  - » If no threads are waiting on the queue, *the signal is remembered for the next thread (i.e., it stores the "wake-up").*
    - – signal() has history
    - – This 'history' is a counter

Semaphore Operations



- Allocate and Initialize
  - » Semaphore contains a non-negative integer value
  - » User cannot read or write value directly after initialization
    - – `sem_t sem;`
    - – `int sem_init( &sem, is_shared, init_value );`
- `wait()` … or *test* or *sleep* or *probe* or *down* or *decrement*.
  - » `P()` for "test" in Dutch (proberen) also `down()`
  - » Waits until semaphore is open (sem>0) then decrement sem value
    - – `int sem_wait( &sem );`
- `signal()` … or *wakeup* or *up* or *increment* or *post*. (done)
  - » V() for "increment" in Dutch (verhogen) also `up()`, `signal()`
  - » Increments value of semaphore, allow another thread to enter
    - – `int sem_post(&sem);`

A Classic Semaphore

```
typedef struct {
        int value;    // Initialized to #resources available
        }semaphore;

sem_wait( semaphore *S )       // Must be executed atomically
        while S->value <= 0;
        S->value--;

sem_signal( semaphore *S )     // Must be executed atomically
        S->value++;
```

- S->value = 0 indicates all resources are used.
  - » Note that S->value is never negative here, this is the classic definition of a semaphore
- Assumption: That there is atomicity between all instructions within the semaphore functions and across (incrementing and the waking up – i.e., you can't perform wait() and signal() concurrently.

Semaphore Implementation (that avoids busy waiting)

```
typedef struct {
        int value;
        queue tlist;            // blocking list of 'waiters'
} semaphore;

sem_wait( semaphore *S )       // Must be executed atomically
        S->value--;
        if (S->value < 0)
               add this process to S->tlist;
               block();

sem_signal( semaphore *S )     // Must be executed atomically
        S->value++;
        if (S->value <= 0)     // Threads are waiting
               remove thread t from S->tlist;
               wakeup(t);
```

Semaphore Example

*What happens when **sem.value** is initialized to 2?*

*Assume **three** threads call sem_wait(&sem)*

```
typedef struct {
        int value;      /* initialize to 2 */
        queue tlist;
} semaphore;
sem_wait( semaphore *S )
        S->value--;
        if (S->value < 0)
           add calling thread to S->tlist;
           block();

sem_signal( semaphore *S )
        S->value++;
        if (S->value <= 0)
          remove a thread t from S->tlist;
          wakeup(t);
```

- Observations?
  - `sem` value is negative (what does the magnitude mean)?
    - Number of waiters on queue
  - `sem` value is positive? What does this number mean, e.g., What is the largest possible value of the semaphore?
    - Number of threads that can be in critical section at the same time

Mutual Exclusion with Semaphores

- Previous example with locks:

```
void deposit( int amount )
  {
  pthread_mutex_lock( &my_lock );
  balance += amount; // critical section
  pthread_mutex_unlock( &my_lock );
  }
```

- Example with Semaphore:

```
void deposit( int amount )
  {
  sem_wait( &sem );
  balance += amount; // critical section
  sem_post( &sem );
  }
```

*What value should **sem** be initialized to provide ME?*

Beware: OS Provided Semaphores

- **Strong Semaphores**: **Order** in semaphore is specified (what we saw, and what most OSs use). FCFS.
- **Weak Semaphore**: Order in semaphore definition is left unspecified
- *Something to think about:*
  - *Do these types of semaphores **solve** the Critical Section Problem? Why or Why not?*

Danger Zone Ahead

Dangers with Semaphores

- Deadlock:
  - Two or more threads are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Example:
  - Two threads: Maria and Tucker
  - Two semaphores: `semA`, and `semB` both initialized to 1

Thread Maria

```
sem_wait( semA )
sem_wait( semB )


sem_post( semA );
sem_post( semB );
```

Thread Tucker

```
sem_wait( semB )
sem_wait( semA )


sem_post( semB );
sem_post( semA );
```


Semaphore Jargon

- Binary semaphore is sufficient to provide mutual exclusion (restriction)
  - Binary semaphore has boolean value (not integer)
  - bsem_wait(): Waits until value is 1, then sets to 0
  - bsem_signal(): Sets value to 1, waking one waiting process
- General semaphore is also called counting semaphore.

Semaphore Verdict

- **Advantage:**
  - » Versatile, can be used to solve any synchronization problems!
- **Disadvantages:**
  - » Prone to bugs (programmers' bugs)
  - » Difficult to program: no connection between semaphore and the data being controlled by the semaphore
- **Consider alternatives: Monitors, for example, provides a better connection (data, method, synchronization)**

- **Next will look at:**
  - » synchronization problems &
  - » start on deadlock
  - » System call in MINIX and adding a service

Classes of Synchronization Problems (Thu)

- **Uniform resource usage with simple scheduling constraints**
  - » No other variables needed to express relationships
  - » Use one semaphore for every constraint
  - » Examples: producer/consumer
- **Complex patterns of resource usage**
  - » Cannot capture relationships with only semaphores
  - » Need extra state variables to record information
  - » Use semaphores such that
    - – One is for mutual exclusion around state variables
    - – One for each class of waiting
- **Always try to cast problems into first, easier type**

Classical Problems: *Readers Writers*

Set of problems where data structures, databases or file systems are read and modified by concurrent threads

- **Idea:**
  - » While data structure is updated (write) often necessary to bar other threads from reading
- ***Basic* Constraints (Bernstein's Condition):**
  - » Any number of readers can be in CS simultaneously
  - » Writers must have exclusive access to CS
- **Some Variations:**
  - » First Readers: No reader kept waiting unless a writer already in CS - so no reader should wait for other readers if a writer is waiting already (reader priority)
  - » Second Readers: Once a writer is ready the writer performs write as soon as possible (writer priority)

First Readers: Initialization

- **First readers: simplest reader/writer problem**
  - » requires no reader should wait for other readers to finish even if there is a writer waiting.
  - » Writer is easy – it gets in if the room is available
- **Two semaphores both initialized to 1**
  - » Protect a counter
  - » Keep track of "room" is empty or not

```
int reader = 0              // # readers in room
sem_t mutex;                // mutex to protect counter
sem_t roomEmpty;            // 1 (true) if no threads and 0 otherwise
int sem_is_shared = 0;      // both threads accesses semaphore

sem_init( &mutex, sem_is_shared, 1 );
sem_init( &roomEmpty, sem_is_shared, 1 );
```


First Reader: Entrance/Exit *Writer*

```
void enterWriter()

sem_wait(&roomEmpty)
```

```
void exitWriter()
     sem_post( &roomEmpty );
```

- **Writer can only enter if it possesses the lock (room is empty)**

First Reader: Entrance/Exit Reader

```
void enterReader()
  sem_wait(&mutex);
    reader++;
    if( reader == 1 )
       sem_wait( &roomEmpty );  // first in locks
  sem_post( &mutex );
```

```
void exitReader()
  sem_wait(&mutex) ;
    reader--;
    if( reader == 0 )
       sem_post( &roomEmpty );  // last out unlocks
  sem_post( &mutex );
```

- Only one reader is queued on roomEmpty, but several writers may be queued
- When a reader signals roomEmpty no other readers are in the room (the room is empty)

First Reader: Entrance/Exit Reader

```
void enterReader()
  sem_wait(&mutex)
    reader++;
    if( reader == 1 )
       sem_wait( &roomEmpty );  // first on in locks
  sem_post( &mutex );
```

```
void enterWriter()
  sem_wait(&roomEmpty)
```

```
void exitWriter()
  sem_post(&roomEmpty);
```

```
void exitReader()
  sem_wait(&mutex)
    reader--;
    if( reader == 0 )
       sem_post( &roomEmpty );  // last unlocks
  sem_post( &mutex );
```

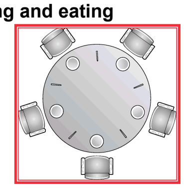
- Only one reader is queued on roomEmpty
- When a reader signals roomEmpty no other readers are in the room
- Writers Starve? Readers Starve? Both?

Classical Problems: *Dining Philosophers*

Classic Multiprocess synchronization that stemmed from five computers competing for access to five shared tape drive peripherals.

- Problem Definition Statement:
  - N Philosophers sitting at a round table
  - Each philosopher shares a chopstick (a shared resource) with neighbor
  - Each philosopher must have both chopsticks to eat
  - Neighbors can't eat simultaneously
  - Philosophers alternate between thinking and eating

```
void philosopher( int i )
  while(1)
     think()
     take_chopstick(i);
     eat();
     put_chopstick(i);
```



Beware of the Imposters

Dining Philosophers

```
void philosopher( int i )
  while(1)
     think()
     take_chopstick(i);
     eat();
     put_chopstick(i);
```

- Two neighbors can't use chopstick at same time
- Must test if chopstick is there and grab it atomically
  - Represent each chopstick with a semaphore
  - Grab right chopstick then left chopstick
  - `sem_t chopstick[5]; // Initialize each to 1`

```
take_chopstick( int i )
   sem_wait( &chopstick[i] );
   sem_wait( &chopstick[(i+1) % 5] );
```

```
put_chopstick( int i )
   sem_post( &chopstick[i] );
   sem_post( &chopstick[(i+1) % 5] );
```

- Guarantees no two neighbors eats simultaneously
- Does this work? Why or Why Not?
- What happens if *all* philosophers wants to eat and grabs the left chopstick (at the same time)?
- Is it efficient? – (assuming we are lucky and it doesn't deadlock)?

Dining Philosophers: *Attempt 2*

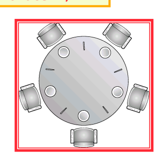
- Add a mutex to ensure that a philosopher gets both chopsticks.

```
take_chopstick( int i )
   sem_wait( &chopstick[i] );
   sem_wait( &chopstick[(i+1) % 5] );
```

```
put_chopstick( int i )
  sem_post( &chopstick[i] );
  sem_post( &chopstick[(i+1) % 5] );
```

```
void philosopher( int i )
  while(1)
     think()
     sem_wait( &mutex );
     take_chopstick(i);
     eat();
     put_chopstick(i);
     sem_post( &mutex )
```

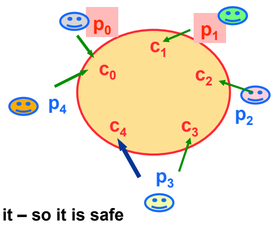
- Problems?
  - How many philosophers can dine at one time?
  - How many should be able to eat?



Dining Philosophers: *Attempt 3*

- Grab lower-numbered chopstick first, then higher-numbered

```
take_chopstick( int i )
  if( i < 4 )
    sem_wait( &chopstick[i] );      //* Right
    sem_wait( &chopstick[(i+1)] ); //* Left
  else
    sem_wait( &chopstick[0] );      //* Left
    sem_wait( &chopstick[4] );      //* Right
```



- Problems?
  - » Safe: Deadlock? Asymmetry avoids it – so it is safe
- Performance (concurrency?)
  - » P_0 and P_4 grabs chopstick simultaneously - assume P_0 wins
  - » P_3 can now eat but P_0 and P_1 are not eating even if they don't share a chopstick with P_3 (so it is not as concurrent as it could be)

What todo: Dining Philosophers: *Dijkstra*

- Guarantees the two goals (helps to solve the problem):
  - » Safety (mutual exclusion): Ensure nothing bad happens (don't violate constraints of problem)
  - » Liveness (progress) : Ensure something good happens when it can (make as much progress as possible)
- Introduce state variable for each philosopher `i`
  - » `state[i] = THINKING, HUNGRY, or EATING`
- Safety: No two adjacent philosophers eat simultaneously (ME)
  - » `for all i: !(state[i]==EATING && state[i+1%5] == EATING)`
- Liveness: No philosopher is HUNGRY *unless* one of his neighbors is eating
  - » Not the case that a philosopher is hungry and his neighbors are not eating --
  - » `for all i: !(state[i]==HUNGRY && (state[i+4%5]!=EATING && state[i+1%5]!=EATING))`

Dining Philosophers: *Dijkstra*

```
sem_t mayEat[5] = {0};              // permission to eat (testS… grants)
sem_t mutex = {1} ;                 // how to init
int state[5] = {THINKING};

take_chopsticks(int i)
  sem_wait( &mutex );               // enter critical section
  state[i] = HUNGRY;
  testSafetyAndLiveness(i);         // check for permission
  sem_post( &mutex );               // exit critical section
  sem_wait(&mayEat[i]);

put_chopsticks(int i)
  sem_wait(&mutex);                 // enter critical section
  state[i] = THINKING;
  testSafetyAndLiveness(i+1 %5);   // check if left neighbor can run now
  testSafetyAndLiveness(i+4 %5);   // check if right neighbor can run now
  sem_post(&mutex);                 // exit critical section

testSafetyAndLiveness(int i)
  if( state[i]==HUNGRY && state[i+4%5]!= EATING&&state[i+1%5]!= EATING )
        state[i] = EATING;
        sem_post( &mayEat[i] );
```


- http://www.doc.ic.ac.uk/~jnm/concurrency/classes/Diners/Diners.html

Monitors

- Motivation:
  - » Users can inadvertently misuse locks and semaphores (e.g., never unlock a mutex)
- Idea:
  - » Languages construct that control access to shared data
  - » Synchronization added by compiler, enforced at runtime
- Monitor encapsulates
  - » Shared data structures
  - » Methods
    - – that operates on shared data structures
  - » Synchronization between concurrent method invocations
- Protects data from unstructured data access
- Guarantees that threads accessing its data through its procedures interact only in legitimate ways